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REFLECTION FACTOR FROM THE PLANE-STRATIFIED MEDIUM OF LUNNITE FOR VARIOUS ANGLES OF INCIDENCE OF ELECTROMAGNETIC WAVES

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ABSTRACT

The reflection factor from a nonuniform inhomogenous medium of plane-stratified nature is computed for the case when this medium's index of refraction varies from a certain value on the surface to another value in depth along the exponential curve.

It is shown that the angular dependence of the reflection factor of such a medium coincides well with that of an homogenous medium for a certain effective value of the index of refraction, determined from the condition of equality of these media's reflections factors when the incidence of electromagnetic waves is normal. Inasmuch as the reflection factor of a stratified medium is dependent on wavelength, the effective reflection factor is also a function of λ.

An approximation is obtained of the frequency dependence of the effective index of refraction as a function of inhomogeneity depth. The applicability is concluded of Fresnel formulas for the calculation of integral Moon's radioemission regardless of the existence of well known inhomogeneity of properties in depth.

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As is well known, the integral radioemission of the Moon is observed in most of cases. This is why for the interpretation of experimental data the elaboration of a corresponding theory is required; it has been worked out in the works under ref. [1-4]. What must be known in particular is the distribution law of the reflection factor along the lunar disk, which amounts to the requirement of knowledge of reflection factor's dependence on the angle of incidence of the waves.

(*) KOEFFITSIENT OTRAZHENIYA OT POSKOSLOISTOY SREDY LUNITA DLYA RAZLICHNYKH UGLOV PADENIYA ELEKTROMAGNITNYKH VOLN.

In connection with the inhomogeneity of properties in depth revealed at the surface of the Moon [5, 6], there arises the question of calculation of reflection factor's dependence upon the wave's incidence angle for an inhomogenous plane-stratified medium, and of ascertaining to what extent it may depart for the earlier utilized dependence for a uniform medium described by the Fresnel formula. This is precisely the object of the present work.

The case was considered in [6] of normal wave incidence in one-dimensional inhomogenous nonabsorbing medium. The accounting of absorption for the lunar surface does not affect the result, for the wave damping in an inhomogenous medium is found to be negligibly small. The calculation of the reflection factor from such a medium is performed in the present work as a function of the angle of incidence applicably to two construction models of Moon's upper layer considered in ref. [6].

In this calculation we shall utilize the equation for reflection factors [7], written for its easy solution on a computer in the form

$$\frac{dR}{dx} = \Gamma(x)(1 - R^2)\cos\varphi,$$
$$\frac{d\varphi}{dx} = -2\beta(x) - \frac{\Gamma(x)}{R}(1 + R^2)\sin\varphi, \qquad (1)$$

where R is the modulus of the reflection factor, ϕ is its phase, $\beta(x) = k_0\sqrt{n^2(x) - \sin^2 i}$, $\Gamma(x) = q'/2q$, $q = \beta|m$ ($m - 1$ for the horizontally polarized wave, $m = n^2(x)$ for a vertically polarized wave) $q' = dq/dx$, i is the incidence angle of the wave, k(0) is the wave number. The index of refraction n(x) is written in the form [6]

$$n(x) = 1 + n_0[1 - (1 - \xi)e^{-x/x_0}]. \qquad (2)$$

According to the considerations stated in the work [6], the initial condition for the solution of Eqs(1) is written in the form

$$R_{\text{нач}} = \int_{\infty}^{x_1} \Gamma(x)\,dx, \qquad (3)$$
$$\varphi_{\text{нач}} = \pi.$$

the subscript 'нач' standing for "initial".

We compiled in Table 1 the results of calculations of the reflection factor by the power of R^2 for various angles of incidence i and wavelengths equal to 3, 10, 30 and 70 cm (for two models of Moon's upper layer construction [6]) for x_0 = 1.5, and in Table 2 for x_0 = 3 cm. The families of computed curves $R^2(i)$ for x_0 = 1.5 cm are plotted in Fig.1.

It is apparently appropriate to introduce an effective index of refraction that would allow us to determine the dependence $R^2(i)$ for various angles λ and x_0 computed by the Fresnel formulas

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$$R_{\perp}^2 = \left[\frac{\cos i - \sqrt{n_{эфф}^2(\lambda, x_0) - \sin^2 i}}{\cos i + \sqrt{n_{эфф}^2(\lambda, x_0) - \sin^2 i}}\right]^2,$$

$$R_{\parallel}^2 = \left[\frac{n_{эфф}^2(\lambda, x_0)\cos i - \sqrt{n_{эфф}^2(\lambda, x_0) - \sin^2 i}}{n_{эфф}^2(\lambda, x_0)\cos i + \sqrt{n_{эфф}^2(\lambda, x_0) - \sin^2 i}}\right]^2, \tag{4}$$

without resorting to the solution of the system of differential equations (1). $R_{\perp}^2$ and $R_{\parallel}^2$ are respectively the reflection factors for the horizontally and vertically polarized wave.

The effective value of the index of refraction is found from the condition of equality of the reflection factors computed by (4) and (1) for a normal wave incidence; then

$$n_{эфф}^2(\lambda, x_0) = \left[\frac{1+R^2}{1-R^2} + \sqrt{\left(\frac{1+R^2}{1-R^2}\right)^2 - 1}\right]^2. \tag{5}$$

where R^2 is the computed value of the reflection factor from (1), which must be taken from the table compiled in the work [6]. The results of calculations of n $n_{эфф}^2(\lambda, x_0)$ are compiled in Table 3. The reflection factor in the function of i and $n_{эфф}^2(\lambda, x_0)$ for $\lambda = 10$, 30, 70 cm and $x_0 = 1.5$ cm, computed by formulas (4) is plotted by dots in Figs.1 and 2, where the exact values of R (i) computed by (1) are also brought out. Comparison of the results of calculations of the dependence of the reflection factor on the angle of incidence of the wave shows that for a stratified medium, this dependence is described with sufficient precision by the Fresnel formulas for the equivalent value of the index of refraction determined from (5). The greatest discrepancy constitutes 3 to 4 percent. Utilizing the dependence of R^2 on λ, obtained by calculation from (1), we may write an empirical formula for the effective value of the index of refraction in the form

$$n_{эфф}^2(\lambda, x_0) = n_3^2 - (n_3^2 - n_2^2)e^{-\alpha\lambda/x_0}, \tag{6}$$

where n_2 and n_3 are respectively the indices of refraction on the surface and in depth of the layer, α is a factor found from the condition

$$e^{-\alpha\lambda_{av}/x_0} = 0.5;$$

λ_{av} being equal to 30 – 35 cm, is the average wavelength of the transitional interval in which the reflection factor varies from its minimum value in centimeter waves to the maximum value at the borderline of decimeter waves (see [6]). Consequently,

$$a = \frac{-x_0 \ln 0.5}{\lambda_{av}} = \frac{0.7\, x_0}{\lambda_{av}} \approx 0.033. \tag{7}$$

TABLE 1

φ, deg.	λ = 3 см				λ = 10 см				λ = 30 см				λ = 70 см			
	$\varepsilon_2 = 1.7$ $\varepsilon_3 = 2.25$		$\varepsilon_2 = 2.25$ $\varepsilon_3 = 3.2$		$\varepsilon_2 = 1.7$ $\varepsilon_3 = 2.25$		$\varepsilon_2 = 2.25$ $\varepsilon_3 = 3.2$		$\varepsilon_2 = 1.7$ $\varepsilon_3 = 2.25$		$\varepsilon_2 = 2.25$ $\varepsilon_3 = 3.2$		$\varepsilon_2 = 1.7$ $\varepsilon_3 = 2.25$		$\varepsilon_2 = 2.25$ $\varepsilon_3 = 3.2$	
	$R^2_\perp$	$R^2_\parallel$	$R^2_\perp$	$R^2_\parallel$	$R^2_\perp$	$R^2_\parallel$	$R^2_\perp$	$R^2_\parallel$	$R^2_\perp$	$R^2_\parallel$	$R^2_\perp$	$R^2_\parallel$	$R^2_\perp$	$R^2_\parallel$	$R^2_\perp$	$R^2_\parallel$
0	0.0177	0.0177	0.0405	0.0405	0.0214	0.0214	0.0471	0.0471	0.0309	0.0309	0.0626	0.0626	0.0374	0.0374	0.0755	0.0755
5	0.0179	0.0175	0.0410	0.0402	0.0217	0.0212	0.0475	0.0466	0.0312	0.0306	0.0632	0.0621	0.0377	0.0370	0.0761	0.0748
10	0.0185	0.0169	0.0423	0.0390	0.0225	0.0205	0.0490	0.0453	0.0323	0.0297	0.0651	0.0604	0.0390	0.0359	0.0782	0.0729
15	0.0197	0.0159	0.0445	0.0370	0.0239	0.0193	0.0515	0.0430	0.0342	0.0281	0.0682	0.0577	0.0411	0.0340	0.0817	0.0697
20	0.0214	0.0145	0.0479	0.0342	0.0260	0.0177	0.0553	0.0398	0.0370	0.0259	0.0729	0.0538	0.0442	0.0313	0.0869	0.0651
25	0.0239	0.0126	0.0526	0.0305	0.0289	0.0156	0.0606	0.0357	0.0410	0.0230	0.0799	0.0488	0.0486	0.0278	0.0910	0.0592
30	0.0273	0.0104	0.0590	0.0261	0.0331	0.0129	0.0678	0.0307	0.0464	0.0195	0.0881	0.0426	0.0546	0.0236	0.1035	0.0520
35	0.0321	0.0078	0.0675	0.0209	0.0388	0.0099	0.0773	0.0249	0.0538	0.0153	0.0995	0.0353	0.0627	0.0187	0.1160	0.0435
40	0.0387	0.0051	0.0789	0.0152	0.0466	0.0066	0.0900	0.0184	0.0637	0.0108	0.1145	0.0271	0.0735	0.0133	0.1321	0.0339
45	0.0480	0.0024	0.0942	0.0093	0.0574	0.0034	0.1068	0.0116	0.0773	0.0062	0.1340	0.0183	0.0881	0.0078	0.1529	0.0236
50	0.0611	0.0005	0.1148	0.0040	0.0726	0.0008	0.1292	0.0054	0.0958	0.0022	0.1595	0.0099	0.1078	0.0030	0.1798	0.0134
55	0.0799	0.0005	0.1428	0.0007	0.0942	0.0004	0.1592	0.0011	0.1213	0.0003	0.1928	0.0032	0.1346	0.0002	0.2146	0.0048
60	0.1075	0.0047	0.1808	0.0021	0.1251	0.0043	0.1995	0.0016	0.1567	0.0029	0.2366	0.0009	0.1716	0.0021	0.2597	0.0004
65	0.1484	0.0175	0.2332	0.0130	0.1700	0.0172	0.2542	0.0116	0.2064	0.0149	0.2943	0.0794	0.2227	0.0135	0.3183	0.0052
70	0.2100	0.0474	0.3055	0.0422	0.2358	0.0478	0.3283	0.0402	0.2767	0.0450	0.3703	0.0334	0.2940	0.0431	0.3945	0.0283
72	0.2428	0.0673	0.3418	0.0624	0.2701	0.0681	0.3649	0.0601	0.3124	0.0658	0.4070	0.0521	0.3297	0.0634	0.4311	0.0460
74	0.2816	0.0939	0.3830	0.0895	0.3103	0.0953	0.4063	0.0871	0.3534	0.0926	0.4481	0.0778	0.3710	0.0906	0.4716	0.0708
76	0.3277	0.1293	0.4300	0.1256	0.3572	0.1314	0.4532	0.1230	0.4007	0.1288	0.4940	0.1127	0.4181	0.1268	0.5166	0.1048
78	0.3824	0.1761	0.4837	0.1733	0.4121	0.1789	0.5061	0.1707	0.4551	0.1765	0.5452	0.1594	0.4720	0.1747	0.5666	0.1507
80	0.4472	0.2379	0.5447	0.2362	0.4764	0.2414	0.5659	0.2336	0.5176	0.2394	0.6023	0.2215	0.5336	0.2375	0.6219	0.2121
82	0.5239	0.3193	0.6142	0.3186	0.5514	0.3232	0.6334	0.3161	0.5896	0.3216	0.6659	0.3037	0.6041	0.3199	0.6832	0.2911
84	0.6149	0.4265	0.6933	0.4266	0.6393	0.4306	0.7095	0.4243	0.6722	0.4294	0.7367	0.4124	0.6845	0.4278	0.7511	0.4030
86	0.7227	0.5677	0.7831	0.5684	0.7418	0.5715	0.7953	0.5665	0.7670	0.5706	0.8155	0.5561	0.7764	0.5693	0.8261	0.5479
88	0.8502	0.7539	0.8849	0.7543	0.8612	0.7565	0.8917	0.7434	0.8757	0.7559	0.9030	0.7465	0.8810	0.7551	0.9088	0.7412
90	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

TABLE 2

i, deg.	λ = 3 см				λ = 10 см				λ = 30 см				λ = 70 см			
	$\varepsilon_2 = 1.7$ $\varepsilon_3 = 2.25$		$\varepsilon_2 = 2.25$ $\varepsilon_3 = 3.2$		$\varepsilon_2 = 1.7$ $\varepsilon_3 = 2.25$		$\varepsilon_2 = 2.25$ $\varepsilon_3 = 3.2$		$\varepsilon_2 = 1.7$ $\varepsilon_3 = 2.25$		$\varepsilon_2 = 2.25$ $\varepsilon_3 = 3.2$		$\varepsilon_2 = 1.7$ $\varepsilon_3 = 2.25$		$\varepsilon_2 = 2.25$ $\varepsilon_3 = 3.2$	
	$R^2_\perp$	$R^2_\parallel$	$R^2_\perp$	$R^2_\parallel$	$R^2_\perp$	$R^2_\parallel$	$R^2_\perp$	$R^2_\parallel$	$R^2_\perp$	$R^2_\parallel$	$R^2_\perp$	$R^2_\parallel$	$R^2_\perp$	$R^2_\parallel$	$R^2_\perp$	$R^2_\parallel$
0	0.0172	0.0172	0.0403	0.0403	0.0183	0.0183	0.0419	0.0419	0.0236	0.0236	0.0503	0.0503	0.0321	0.0321	0.0648	0.0648
5	0.0174	0.0170	0.0407	0.0399	0.0185	0.0181	0.0424	0.0415	0.0239	0.0234	0.0508	0.0498	0.0325	0.0318	0.0654	0.0643
10	0.0180	0.0164	0.0420	0.0387	0.0192	0.0174	0.0437	0.0403	0.0248	0.0227	0.0523	0.0484	0.0336	0.0309	0.0673	0.0626
15	0.0191	0.0154	0.0442	0.0366	0.0203	0.0164	0.0460	0.0382	0.0263	0.0214	0.0551	0.0461	0.0355	0.0292	0.0706	0.0598
20	0.0208	0.0140	0.0474	0.0337	0.0221	0.0149	0.0494	0.0352	0.0286	0.0196	0.0591	0.0428	0.0384	0.0269	0.0751	0.0558
25	0.0232	0.0121	0.0520	0.0310	0.0247	0.0130	0.0542	0.0314	0.0319	0.0173	0.0647	0.0385	0.0425	0.0240	0.0820	0.0506
30	0.0264	0.0099	0.0582	0.0255	0.0282	0.0107	0.0607	0.0268	0.0364	0.0145	0.0722	0.0332	0.0481	0.0203	0.0908	0.0442
35	0.0310	0.0074	0.0666	0.0203	0.0331	0.0080	0.0691	0.0214	0.0426	0.0112	0.0823	0.0270	0.0556	0.0160	0.1025	0.0367
40	0.0373	0.0047	0.0778	0.0145	0.0390	0.0052	0.0810	0.0154	0.0511	0.0077	0.0956	0.0202	0.0658	0.0113	0.1177	0.0283
45	0.0461	0.0021	0.0927	0.0086	0.0494	0.0024	0.0965	0.0093	0.0628	0.0041	0.1132	0.0130	0.0796	0.0065	0.1376	0.0193
50	0.0587	0.0003	0.1129	0.0034	0.0629	0.0004	0.1174	0.0038	0.0791	0.0012	0.1365	0.0063	0.0984	0.0024	0.1634	0.0105
55	0.0768	0.0004	0.1403	0.0002	0.0822	0.0004	0.1457	0.0004	0.1020	0.0003	0.1675	0.0015	0.1242	0.0002	0.1970	0.0034
60	0.1034	0.0047	0.1778	0.0018	0.1104	0.0047	0.1842	0.0017	0.1346	0.0040	0.2089	0.0013	0.1600	0.0027	0.2411	0.0007
65	0.1431	0.0175	0.2285	0.0129	0.1522	0.0177	0.2339	0.0126	0.1812	0.0167	0.2646	0.0107	0.2101	0.0146	0.2990	0.0074
70	0.2034	0.0472	0.3012	0.0424	0.2147	0.0479	0.3095	0.0420	0.2487	0.0472	0.3394	0.0386	0.2806	0.0445	0.3751	0.0324
72	0.2356	0.0671	0.3372	0.0627	0.2478	0.0680	0.3158	0.0622	0.2836	0.0676	0.3762	0.0583	0.3164	0.0649	0.4119	0.0509
74	0.2740	0.0935	0.3784	0.0899	0.2370	0.0949	0.3871	0.0894	0.3242	0.0949	0.4176	0.0850	0.3575	0.0922	0.4528	0.0764
76	0.3197	0.1287	0.4253	0.1261	0.3333	0.1305	0.4311	0.1257	0.3714	0.1310	0.4642	0.1208	0.4047	0.1284	0.4985	0.1111
78	0.3740	0.1754	0.4790	0.1740	0.3383	0.1776	0.4876	0.1735	0.4262	0.1786	0.5167	0.1683	0.4590	0.1761	0.5495	0.1577
80	0.4388	0.2370	0.5402	0.2368	0.4528	0.2396	0.5484	0.2354	0.4900	0.2412	0.5759	0.2309	0.5214	0.2389	0.6063	0.2197
82	0.5160	0.3182	0.6101	0.3192	0.5293	0.3212	0.6175	0.3189	0.5642	0.3232	0.6423	0.3134	0.5930	0.3212	0.6694	0.3018
84	0.6078	0.4253	0.6896	0.4273	0.6197	0.4284	0.6961	0.4270	0.6503	0.4308	0.7170	0.4218	0.6751	0.4290	0.7396	0.4106
86	0.7170	0.5666	0.7802	0.5589	0.7264	0.5693	0.7851	0.5687	0.7503	0.5716	0.8008	0.5642	0.7693	0.5703	0.8176	0.5545
88	0.8465	0.7531	0.8832	0.7549	0.8521	0.7550	0.8850	0.7548	0.8661	0.7565	0.8948	0.7519	0.8770	0.7557	0.9041	0.7455
90	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

TABLE 3

λ, см	$\varepsilon_2 = 1{,}7;\ \varepsilon_3 = 2{,}25$								$\varepsilon_2 = 2{,}25;\ \varepsilon_3 = 3{,}2$							
	$x_0 = 1$ см		$x_0 = 1{,}5$ см		$x_0 = 2$ см		$x_0 = 3$ см		$x_0 = 1$ см		$x_0 = 1{,}5$ см		$x_0 = 2$ см		$x_0 = 3$ см	
	(*) $\varepsilon_{эфф}$	(**) $\varepsilon_{эфф.выч.}$	$\varepsilon_{эфф}$	$\varepsilon_{эфф.выч.}$	$\varepsilon_{эфф}$	$\varepsilon_{эфф.выч.}$	$\varepsilon_{эфф}$	$\varepsilon_{эфф.выч.}$	$\varepsilon_{эфф}$	$\varepsilon_{эфф.выч.}$	$\varepsilon_{эфф}$	$\varepsilon_{эфф.выч.}$	$\varepsilon_{эфф}$	$\varepsilon_{эфф.выч.}$	$\varepsilon_{эфф}$	$\varepsilon_{эфф.выч.}$
1	1.74	1.72	1.74	1.71	1.74	1.71	1.74	1.71	2.25	2.28	2.25	2.27	2.25	2.26	2.25	2.26
2	1.78	1.73	1.78	1.72	1.78	1.72	1.78	1.71	2.25	2.31	2.25	2.29	2.25	2.28	2.25	2.27
3	1.78	1.75	1.78	1.74	1.78	1.73	1.78	1.72	2.27	2.34	2.27	2.31	2.27	2.29	2.27	2.28
4	1.80	1.77	1.78	1.75	1.78	1.73	1.78	1.72	2.30	2.37	2.27	2.33	2.27	2.31	2.27	2.29
6	1.84	1.80	1.80	1.77	1.78	1.75	1.78	1.74	2.34	2.42	2.30	2.37	2.27	2.34	2.27	2.31
10	1.91	1.85	1.84	1.81	1.80	1.78	1.78	1.76	2.41	2.52	2.36	2.44	2.30	2.39	2.27	2.35
20	2.05	1.97	1.97	1.90	1.91	1.85	1.84	1.81	2.63	2.71	2.53	2.59	2.43	2.50	2.36	2.44
30	2.13	2.05	2.05	1.97	1.99	1.90	1.91	1.85	2.81	2.85	2.66	2.71	2.57	2.60	2.43	2.52
40	2.17	2.10	2.10	2.02	2.05	1.95	1.97	1.90	2.90	2.95	2.79	2.81	2.66	2.69	2.55	2.59
60	2.20	2.17	2.17	2.10	2.13	2.03	2.05	1.97	2.97	3.07	2.90	2.45	2.81	2.82	2.66	2.71
100	2.22	2.23	2.20	2.19	2.20	2.13	2.15	2.07	3.03	3.16	3.00	3.09	3.45	3.00	2.83	2.88
200	2.25	2.25	2.25	2.25	2.25	2.23	2.22	2.19	3.05	3.20	3.05	3.19	3.05	3.16	3.00	3.03

$\varepsilon_{эфф}$ stands for ε_{eff} (experim) (see (*), odd columns)

$\varepsilon_{эфф.выч.}$ stands for ε_{eff} (computed) (see (**) even columns)

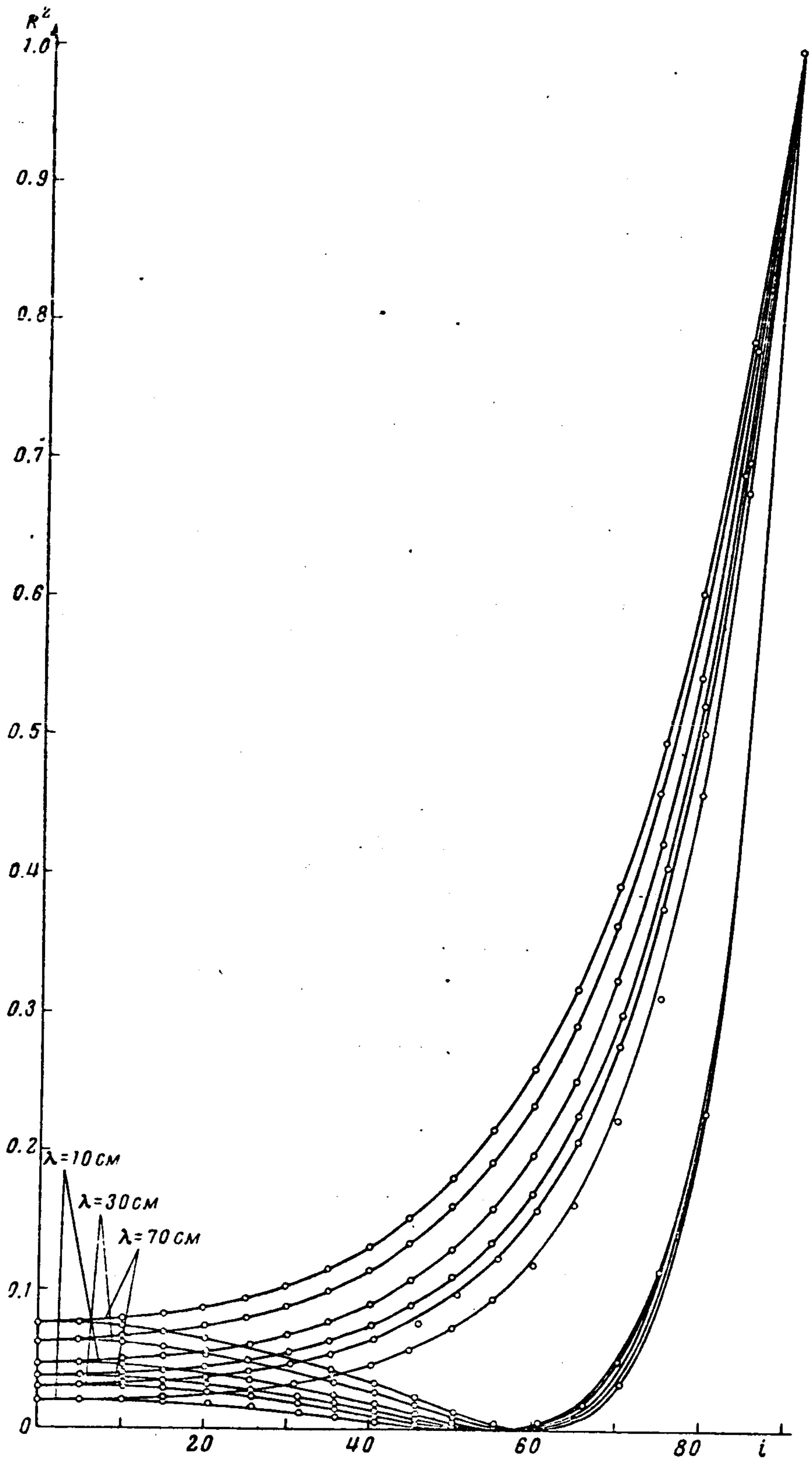

Fig.1

The values of $n^2_{эфф}(\lambda, x_0)$ computed by formula (6), agree well with the values obtained from (5) (see Table 3).

Therefore, expressions (4) and (6) allow us to compute the reflection factor $R^2(i)$ for various values of λ, x_0, n_2^2 and n_3^2 of a plane-parallel nonabsorbing medium at least in the range of investigated values of x_0 and n.

In conclusion I wish to express my gratitude to V. S. Troitskiy, R. E. Erm and I. I. Malova for their help in the work.

****** THE END ******

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